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# DOCUMENT

## PACS Spectrometer: dealing with “contaminated” off-source data

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## 1 INTRODUCTION

This technical note is coupled with the “On-source/Off-source” HPDP PACS spectroscopy products and their accompanying release note. These products are available from the HSA and from the [HPDP portal](#) on the HSC website, and the release note and processing scripts can be found in the [Legacy repository](#) area.

For the vast majority of PACS spectroscopy observations processed by the SPG pipelines and provided via the HSA, the science-grade products have been background subtracted: the background as observed at an off-source position has been subtracted from the source+background as observed at the on-source position. It is therefore not always easy to inspect the on-source and off-source data separately. To allow for an easy inspection of the two, on-source and off-source cubes were created for each observation in the HSA and they are provided as the On/Off HPDP. The use-case of these HPDPs is primarily inspection for emission in the off-source position. If any emission is found, then whether this is “contamination” (in the sense that this emission is in the off-source position only, and hence *ought not* to have been subtracted by the pipeline) or not (i.e. it indeed *should have* been subtracted), it may be the case that the SPG products provided by the HSA are *not* suitable for science use. In these cases it will be necessary to use alternative products, with the choices being: the on/off HPDP cubes, cubes created by the on/off HPDP scripts or by an interactive pipeline in HIPE, and in all cases potentially with some data manipulation by the scientist.

In this technical note we explain what to do if you do find off-source emission in your observation.

Before reading this technical note you should be familiar with PACS spectroscopy, in particular with the various observing modes that were used and different types of cubes that were produced. These are explained in the [Quick-Start Guide](#), and in more detail in the [PACS Products Explained](#) and the [PACS Handbook](#), all of which can be found in the Herschel Legacy Library ([PACS](#) section). To follow the advice given in this technical note, the user should have at least read the Quick-Start Guide, and should know what observing mode their observation was taken with. Definitions are provided at the end of this technical note, but to *understand* the terms defined, it is necessary to read the other documentation.

## 2 WHY IS OFF-SOURCE EMISSION BAD?

The reason that “extra” off-source emission is bad is related to the way the off-source data are subtracted from the on-source data, to what it is expected that the background spectrum



contains, and to the flux calibration scheme was used to reduce the data.

## 2.1 Flux calibration of PACS spectroscopy data

The flux calibration for PACS spectroscopy is explained in detail in the [PACS Handbook](#). In brief:

- The first calibration method developed was the “Calibration Block and RSRF” scheme, where data of the internal calibration sources taken at the start of every observation are used to flux calibrate the entire observation. The off-source subtraction in this scheme is done either by creating separate on-source and off-source cubes, and at the end of the pipeline subtracting the respective image arrays (unchopped observations); or by an <On-Off> subtraction done on consecutive data-points very early in the pipeline (chop-nod observations).

The final SPG products provided by the HSA for *unchopped observations* were processed with this calibration scheme.

- The “Telescope Normalisation” scheme was later developed for chop-nod observations. In this, the flux calibration is tied to the spectrum of the telescope mirror (which is known and provided as a calibration product). The consecutive data-point subtraction is a ratio –  $\langle (\text{On-Off}) / ((\text{On} + \text{Off}) / 2) \rangle$  – producing off-source subtracted data that are at the same time converted to units of “normalised telescopes”. The conversion to Jy is then done at the end of the pipeline.

The SPG products provided by the HSA for *chop-nod observations* were processed with this calibration scheme.

The telescope normalisation scheme is superior because of the way that it deals with detector response drifts. Detector response drifts could endure for up to hours and could occur in any observation. They were triggered by “bright events”, e.g. after observing a very bright object, or after the grating crossed a bright spectral line within the spectrum of an object, or after the grating was set to a very responsive part of the RSRF. If not dealt with properly, response drifts can lead to an incorrect flux calibration for the data taken during the drift. This is mainly noticeable in the shape of the continuum for SED and long range-scan observations. The telescope normalisation method effectively tracks and corrects for changes to the detector response throughout every measurement, for every second of the observation, because *every* OnOff-subtracted datapoint is tied to the detected telescope spectrum *at that point in time*. The calibration block scheme, however, measures the response at the start of the observation and assumes that it does not drift from then onwards.

Since the telescope normalisation method produces cleaner spectra, it was the calibration scheme finally adopted for chop-nod observations. (Unchopped observations had no consecutive on/off datapoints, and hence that scheme cannot be applied to these data.) However, both schemes are included in the interactive pipeline scripts in HIPE, and a user can process their data with either.



The two schemes return similar results when applied to the same data. However, while some sources of calibration error have the same affect on data produced via the two schemes, not all do. Consequently, when the two schemes are applied to the same data, *differences of up to 15% in the fluxes of the continuum and independently in the integrated fluxes of emission lines should be expected.*

## 2.2 Why off-source emission interferes with the flux calibration

The main contribution to the background of any PACS spectroscopy observation is the telescope mirror. Its flux is high, from 400–150 Jy ( blue to the red: see Fig 1 in the OnOff HPDP release note).

The flux calibration for the unchopped observations – the calibration block scheme – does not “care” whether there is any extra emission in the off-source data over and above that of the telescope spectrum: it simply subtracts the off from the on. Hence, if there is astronomical emission (either spectral lines or continuum) in the off-source position for unchopped observations, the result is simply that this extra is subtracted from the on-source data. Whether this is correct or not depends on the nature of the off-source emission (this being a decision only the scientist can make). Later in this technical note we give advice about what to do in this case.

The flux calibration for chop-nod observations – the telescope normalisation scheme – however requires that the data in the off-source observation are very much dominated by the telescope spectrum. Since the telescope spectrum is bright, this is true for most observations done with PACS spectroscopy. However, it will not be true if there is a noticeable amount of spectral “contamination” in the off-source data. Bear in mind that off-source subtraction in this scheme is a *ratio*, and the presence of emission over and above that of the telescope spectrum in the off-source data leads to an *incorrect flux calibration*. Tests were carried out reducing chop-nod data with line emission in the off-source position, using the calibration block pipeline (which will give the correct subtracted flux levels) and telescope normalisation scheme, and it was found that the flux returned by the telescope normalisation scheme is too low. For these situations, therefore, the telescope normalisation scheme (i.e. the SPG products) should not be used.

When inspecting the On/Off HPDPs for your observation, key to remember is: *if there is emission* in the off-source position, then regardless of whether it is contamination (and so *should not* be subtracted) or whether it is expected (and so *should* be subtracted), the data reduction pipeline that should be used is that using the “Calibration Block and RSRF” scheme.

- For unchopped observations this *is* the calibration scheme that is used by the SPG and the HPDP pipelines.

However, whether the SPG data can be used or not depends on whether the off-source



emission should, or should not, be subtracted.

- For chop-nod observations the SPG products are created by the “Telescope normalisation” scheme, and hence the SPG products should **not** be used for science, whether or not the off-source emission should be subtracted.

Before explaining what to do if off-source emission is found, we will give information on how to use the OnOff HPDP cubes to look for off-source emission. It is assumed that the reader has gotten the HPDP cubes for their observation and is inspecting them already in their favourite cube visualisation software.

### 3 USING THE HPDP TO LOOK FOR OFF-SOURCE EMISISON

#### 3.1 What type of emission can be searched for?

The HPDPs are provided primarily to look for **spectral features**, most commonly emission lines. Spectral lines are easy to find via a simple inspection of the cubes with any cube visualisation software.

To use the HPDP cubes to look for astronomical **continuum emission** in the off-source position is a more difficult prospect because of the higher uncertainty in the continuum, and for one technical reasons:

- For *unchopped observations*, the level of the continuum is very uncertain, with an uncertainty of  $\pm 20$  Jy for each 9.4"-sized spaxel of each rebinned cube. (For mosaic cubes with smaller spaxel sizes, this uncertainty will scale with the relative area.) For very bright sources (with fluxes of many 100's Jy in the continuum) the uncertainty may even reach 50–200 Jy. In most, but not all, cases the unchopped fluxes are too high.
- The uncertainty in the absolute level of the telescope continuum level for any *chop-nod observation* is up to 5 Jy in each spaxel.
- For *chop-nod observations*, the *nodA+nodB* on-source data should be compared to the *nodA+nodB* off-source data, not to the nodA or nodB off-source data separately.

Why is this?

1. The lines of sight through the telescope mirror for the nodA on or off and nodB on or off pointings are different.
2. Since the emission of the mirror varied over its face, the telescope part of the background included in the separated nodA and nodB cubes is slightly different
3. Therefor there is an intrinsic additive difference to continuum flux levels in the nodA and nodB on-source and off-source cubes.

In the HPDPs, the on-source cubes provided are the *nodA+nodB combination*, but the



off-source nodA and nodB cubes are provided *separately*. The continuum of the two off-source cubes will therefore always have a different telescope contribution to each other, and hence any difference in their continuum level (compared to each other and to the on-source cube) will not necessarily be due to an astronomical contribution. This is true even though a telescope spectrum has been subtracted by the HPDP pipeline, because that spectrum subtracted is the *average* of the two nods. Therefore, to inspect for any “extra” continuum in the off-source data, *it will be necessary to first average together the nodA and nodB off-source HPDP cubes*.

### 3.2 Is off-source emission necessarily “contamination”?

If there are *spectral lines* in the off-source data that are at the same location as spectral lines in the on-source data, does this necessarily imply “contamination”? This depends on the source and the science the user wishes to obtain from the data. Whether the lines are contamination or rather a background that should be subtracted depends on the relationship of the emitting source in the off position to the emitting source in the on position. This is a decision that only the scientist can make. To help in the decision-making process, the on-source and off-source cubes can be overlaid on an image (e.g. a PACS image) of the observed field using the PACS Spectral Footprint viewer in HIPE (see the PACS Data Reduction Guide, which is available from the HIPE Help menu or from [the HSC ‘Data Processing’ link](#)). When doing this, bear in mind that the off position for the unchopped observations is a single position on the sky, while for the chop-nod observations they are two equidistant positions either side of the on-source observation. In addition, the off-source and on-source cube spectra can be directly compared to each other in the Spectrum Toolbox in HIPE.

If the *continuum level* in the off-source cube(s) is clearly greater than that in the on-source cube, does this imply an extra continuum emission in the off-source position(s)? The answer depends on how great the difference is. Bear in mind the 20 Jy or more continuum level uncertainty for unchopped observations (on-source and off-source); the ~5Jy continuum level uncertainty, especially for faint sources, for chop-nod observations; and the calibration uncertainty of 15–20% of the measured flux levels, for the continuum as well as for emission lines (see the [Quick-Start Guide](#) for more information) and for all observing modes. still be measured.

## 4 DEALING WITH OFF-SOURCE EMISSION

If you find a *continuum* contribution in the off-source HPDP cube(s) that is in excess of that from the telescope background (and you are very sure it is an excess), and the continuum level of the target is of scientific interest, then the following advice is given:

- If the excess is only a few percent of the telescope background level (i.e. a few Jy: see





Fig. 1 in the HPDP Release Note) then it is best to ignore it, and the SPG products taken from the HSA **should** be used (whatever type of observation you have). A slight extra uncertainty in the flux calibration should then be assumed.

Note that the high uncertainty in the continuum level for unchopped observations means that such a small difference is unlikely to ever be securely identified.

- If the excess is of the order 10% of the telescope background level (i.e. a 10's of Jy), then the SPG products taken from the HSA should **not** be used: it is better here to re-reduce the data using the “calibration block” scheme, for all types of observation. Advice about what do – whether you want to modify the off-source data before subtraction or just skip the background subtraction – is given next.
- If the excess is higher, then it is probably best to skip the background subtraction altogether, because the calibration uncertainties will otherwise be very high. The SPG products taken from the HSA should **not** be used. Advice about what do is given next.

If there are *emission lines* in the off-source HPDP cube(s), then the following advice is given:

- If the line is very faint (or in a spectral range not of interest), you could choose to ignore it. If so, the SPG products taken from the HSA **can** be used (whatever type of observation you have). A slight extra uncertainty in the measured line fluxes should then be assumed.
- But in most cases it will not be acceptable to ignore the lines. In this case it will be necessary to use products created with the “calibration block” scheme. For unchopped observations this is already the case, and whether you should use the SPG or HPDP products, or run a pipeline script in HIPE, depends on how you wish to tackle the contaminating lines. For chop-nod observations it will be necessary to use either the HPDP products or run a pipeline in HIPE following the calibration block scheme. Advice for these cases is given next.

## 5 OFF-SOURCE EMISSION THAT IS NOT “CONTAMINATION”

Let us start with the easier case. If the off-source cubes show emission features (lines, continuum) and the user has established that these features *should indeed* be fully subtracted from the on-source data, which products should be used?

### 5.1 Unchopped observations

For the unchopped mode, the SPG pipeline uses the calibration block method (Secs 2.1 and 2.2), and hence any emission in the off-source position that should be subtracted, has been correctly subtracted. Even if the wavelength, width, or shape of the line in the on-source and off-source positions differ slightly, the *integrated flux* of the residual (background-subtracted) line can still be measured. Hence, the SPG products *can be* used.



## 5.2 Chop-nod observations

For the chop-nod mode, the SPG products *should not* be used if there is noticeable off-source line or continuum emission, *even if* it needs to be fully subtracted from the on-source data. Why is explained in Secs 2.1 and 2.2. Whether to do this or to instead accept the extra uncertainty, is a decision only the scientist can make – it will depend on the relative strength of the contamination compared to the target flux, calibration uncertainties, and SNR.

If deciding to reprocess the data, the user should start from a download from HSA, which they should process from Level 0.5 using the ‘Calibration Block and RSRF’ interactive pipeline script in HIPE. In most cases, it will not be necessary to change anything in this script except saving and visualisation options, and the user will need to choose which of the final products to create (choosing those which are recommended for their type of observation and source: see the [Quick-Start Guide](#) and the [Product Decision Tree](#) for more information). The pipeline scripts can be found in the HIPE ‘Pipeline’ menu. For line-scan and range scan observations of less than about 5  $\mu\text{m}$  range, select from the submenu ‘Chopped line scan & short range scan’. For all other observations go to the ‘Chopped large range scan SEDs’ menu. The pipeline scripts are well annotated, but PACS Data Reduction Guide, which can be accessed from the HIPE Help menu, should also be consulted.

The calibration uncertainty for the calibration block method is higher than for the telescope normalisation method (because of the detector drifts), but this has already been included in the (conservative) calibration uncertainties that are quoted in the [Quick-Start Guide](#). A comparison of the SPG and your own reductions is probably helpful here.

Even if the wavelength, width, or shape of the line in the on-source and off-source positions differ slightly, the *integrated flux* of the residual (background-subtracted) line can still be measured.

## 6 OFF-SOURCE EMISSION THAT IS “CONTAMINATION”

Here we give advice about which cubes to use or to create if the off-source emission *should not be* subtracted, either at all or without first some modification of the off-source spectra. In the advice that follows, you may be required to use the HPDP scripts or another script in HIPE. In this case you will be free to choose which type of cube to create – either the rebinned cubes or one of the mosaic cubes (interpolated or projected, but not drizzled, as is explained later). To know what the recommendations are for the different observing modes and target type, see the [Quick-Start Guide](#) and the [Product Decision Tree](#).



## 6.1 Unchopped observations: do no background subtraction

The easiest option here is to not do a background subtraction at all. The background is an additive contribution and so for emission line contamination, skipping the background subtraction step should not affect the line measurements. The only possible drawback here is that the background shape can be rather structured (bumps and wiggles). A simple comparison of the HPDP on-source spectra to the SPG spectra can show whether or not this will be a problem for the identification of spectral lines for any particular observation.

If choosing to skip the background subtraction:

- *For line-scan observations*, the HPDP on-source cubes can be used. If you want to have a different mosaic cube to that provided in the HPDP, or to work with rebinned cubes (e.g. which are the necessary product for point and semi-extended sources), run the HPDP script in HIPE, and at the end use a different mosaicking task or stop at the point where the rebinned cubes have been finalised.  
Alternatively, run the standard interactive pipeline script in HIPE: this can be found in the ‘Pipeline’ menu, submenu ‘Unchopped line scan’ and then ‘Calibration source and RSRF’. Skip the background subtraction task (`specSubtractOffPosition`), and then either stop (if on-source rebinned cubes are the product you want) or create on-source mosaic cubes. The HPDP script is based on this pipeline script, but that in HIPE is better annotated. The HPDP script also removes an average telescope spectrum from the cubes: this was done for cosmetic reasons and it is OK to skip it.
- *For range-scan observations*, take whichever product you want to work with from the Level 2 of the on-source observation.

## 6.2 Unchopped observations: do a modified background subtraction

For the unchopped observations for which the “extra” off-source emission features (line or continuum) should not be subtracted from the on-source data, but where you find it necessary instead to subtract a modified background, the choice of what to do depends on whether you have line- or range-scan data, pointed or mapping observations. The “modification” is up to the user to do – there are no scripts in HIPE to e.g. cut emission lines out of off-source data, although there are plenty of tasks and code in HIPE that can be used together to do this. Here the advice is limited to which cubes to use and where to get them or how to create them.

### 6.2.1 Line-scan pointed unchopped observations

For line-scan pointed unchopped observations, the HPDP mosaic cubes can be used. The spectra in the off-source cube should be manipulated as desired, and the image arrays of the on-source and modified off-source cubes can then be subtracted from each other.



If it is necessary to create a different type of mosaic cube to that provided as the HPDP, or to produce rebinned cubes instead, the HPDP scripts can be followed, and a different mosaicking task used or the script stopped at the point where the rebinned cubes have been finalised. The off-source manipulation can then be done. Finally, if working with mosaic cubes the images arrays of the off-source and on-source cubes can then be subtracted, if working with rebinned cubes use the standard pipeline task (`specSubtractOffPosition`).

When subtracting the image arrays of on-source and off-source mosaic cubes from each other, bear in mind that their spatial dimensions may not be the same as each other. While all pointed observations do have the sky footprint of the PACS IFU (i.e. a 47"x47" field), in the course of turning them into interpolated cubes they can sometimes end up having very slightly different dimensions (this depends on the position angle of the observation and the need to make a quadrilateral grid). One way to get around this is to re-run the HPDP script to create rebinned cubes (which all have a 5x5 spatial grid), manipulate the off-source cubes as required, do a background subtraction using the standard pipeline task, and then create the mosaic cube. See Sec. 6.2.2 for more advice.

All HPDP cubes created as part of an on-off pair will have the same wavelength grid (and so that dimension will be the same for the two).

### **6.2.2 Line-scan mapping unchopped observations**

For line-scan mapping unchopped observations, subtracting the image arrays of the HPDP mosaic cubes is not necessarily recommended. The key here is that they are *mosaic* cubes: it is better to instead create the rebinned cubes, manipulate the off-source spectra as desired, and then use the standard pipeline task to do the subtraction of the on-source and off-source rebinned cubes (`specSubtractOffPosition`, which can handle mapping and pointed observations seamlessly). The resulting residual rebinned cubes can then be turned into mosaic cubes. The difference between this approach and that of subtracting the HPDP on-source and (manipulated) off-source mosaic cubes directly is an improved SNR and spectral shape. For bright lines this is probably not important, but for middling and fainter lines it could be.

Another limitation to subtracting with the mosaic cubes is that the field covered by the on-source data is whatever the observer requested, but the off-source data were always taken with the FoV of a single pointing: a 47"x47" field. Directly subtracting the (different-sized) image arrays will be difficult, although the user is invited to be creative (e.g. subtract a scaled mean off-source spectrum from the spaxels of the on-source cube?).

Drizzled cubes – which are one of the mosaic cubes produced by the SPG pipelines, but which are not provided as the On/Off HPDP – are created not from the rebinned cubes but those from which the rebinned cubes themselves were created – the so-called *PacsCubes*. These are a *very* complex product. If the user decides they want to manipulate the off-source spectra



before doing a background subtraction of the on-source cubes, they are discouraged from attempting this on PacsCubes; this also means they cannot then create drizzled cubes. The projected cubes are a very good alternative.

### **6.2.3 Range-scan pointed unchopped observations**

For range-scan pointed unchopped observations, the HPDP cubes can be used. The spectra in the off-source cube should be manipulated as desired, and the image arrays of the on-source and modified off-source cubes can then be subtracted from each other.

If it is necessary to create a different type of mosaic cube to that provided as the HPDP, or to produce rebinned cubes instead, the HPDP scripts can be followed, and a different mosaicking task used or the script stopped at the point where the rebinned cubes have been finalised. The off-source manipulation can then be done. Finally, if working with mosaic cubes the images arrays of the off-source and on-source cubes can then be subtracted, if working with rebinned cubes use the standard pipeline task (`specSubtractOffPosition`). Remember that the range-scan mapping unchopped on-source and off-source data were taken as separate observations.

When subtracting the image arrays of on-source and off-source mosaic cubes from each other, bear in mind that their spatial dimensions may not be the same as each other. While all pointed observations do have the sky footprint of the PACS IFU (i.e. a 47"x47" field), in the course of turning them into interpolated cubes they can sometimes end up having very slightly different dimensions (this depends on the position angle of the observation and the need to make a quadrilateral grid). One way to get around this is to re-run the HPDP script to create rebinned cubes (which all have a 5x5 spatial grid), manipulate the off-source cubes as required, do a background subtraction using the standard pipeline task, and then create the mosaic cube. See Sec. 6.2.4 for advice here.

All HPDP cubes created as part of an on-off pair will have the same wavelength grid (and so that dimension will be the same for the two).

### **6.2.4 Range-scan mapping unchopped observations**

For range-scan mapping unchopped observations, the on-source and off-source data are separate observations. It is therefore possible to use the cubes from the Level 2 of the SPG data: manipulate the off-source cube as desired and subtract that from the on-source cube.

Subtracting the image arrays of the *mosaic* cubes taken from the Level 2 is not necessarily recommended. It is better to instead use the HPDP script to create the rebinned cubes, manipulate the off-source spectra as desired, and then use the standard pipeline task to do the subtraction of the on-source and off-source rebinned cubes (`specSubtractOffPosition`, which can handle mapping and pointed observations seamlessly). The resulting residual



rebinned cube can then be turned into a mosaic cube. The difference between this approach and that of subtracting the SPG on-source and (manipulated) off-source mosaic cubes directly is an improved SNR and spectral shape. For bright lines this is probably not important, but for middling and fainter lines it could be.

Another limitation to subtracting with the mosaic cubes is that the field covered by the on-source mapping observation is whatever the observer requested, but the off-source observation was almost always a single pointing: a 47"x47" field. Directly subtracting the (different-sized) image arrays will be difficult, although the user is invited to be creative (e.g. subtract a scaled mean off-source spectrum from the spaxels of the on-source cube?).

### 6.3 Chop-nod observations: do no background subtraction

Here, the easiest option is to not do a background subtraction at all. The background is an additive contribution and so if the science is done with emission lines, skipping the background subtraction step should not affect the line measurements. If the off-source emission lines are in the same location as the on-source emission lines, one could measure the integrated flux of the two separately and subtract them as simple values.

One possible drawback is that the background shape can be rather structured (bumps and wiggles). A simple comparison of the HPDP on-source spectra to the SPG spectra can show whether or not this will be a problem for the identification of spectral lines for any particular observation. Another factor to take into account is that the result of doing no background subtraction may be noisier than the SPG result (less in terms of RMS, more in terms of structured noise).

If choosing the skip the background subtraction:

- *For line-scan observations*, the HPDP on-source cubes can be used. To create a different type of mosaic cube or to create rebinned cubes instead, run the HPDP script in HIPE, and at the end use a different mosaicking task or stop at the point where the rebinned cubes have been finalised.

Alternatively, the HIPE `Split On Off' script (on which the chop-nod HPDP script is based) can be used – this script is annotated and will therefore be easier to understand. From the HIPE `Pipeline' menu, select from the submenu `Chopped line scan & short range scan' for line scans. The HPDP script also removes an average telescope spectrum from the cubes: this was done for cosmetic reasons and it is OK to skip.

- *For range-scan observations*, the same advice applies. If using the `Split On Off' script, that for long range scan observations (longer than about 5  $\mu\text{m}$ ) can be found in the `Pipeline' submenu `Chopped large range scan SEDs'. For the shorter range scans, the submenu `Chopped line scan & short range scan' should be consulted.



## 6.4 Chop-nod observations: do a modified background subtraction

For the chop-nod observations for which the “extra” off-source emission features (line or continuum) should not be subtracted from the on-source data, but where it is necessary instead to subtract a modified background, the choice of what to do depends on the observing mode – pointed or mapping? The “modification” is up to the user to do – there are no scripts in HIPE to e.g. cut emission lines out of off-source data, although there are plenty of tasks and code in HIPE that can be used together to do this. Here the advice is limited to which cubes to use and where to get them or how to create them.

For chop-nod observations, two off-source positions were observed (see e.g. Sec 3.1). What to do if you wish to manipulate the off-source data depends on whether the contamination is present in one or both of the nod positions.

### 6.4.1 Pointed chop-nod observations: both nod positions are contaminated

For pointed chop-nod observations, the HPDP cubes can be used. Since both nod positions are contaminated, you should combine (average) the nodA and nodB off-source cubes and then manipulate the spectra as desired. The image arrays of the on-source and modified off-source cubes can then be subtracted from each other.

If it is necessary to create a different type of mosaic cube to that provided as the HPDP, or to produce rebinned cubes instead, the HPDP script (or the `Split On-Off` script in HIPE, on which the HPDP script is based) can be followed, and a different mosaicking task used or the script stopped at the point where the rebinned cubes have been finalised. The off-source (nodA and nodB) cube averaging and required data manipulation can then be done: if working here with mosaic cubes the on- and off-source images arrays can then be subtracted, if working with rebinned cubes use the standard pipeline task used for unchopped observations (specSubtractOffPosition: with some manipulation necessary to set appropriate on-source and off-source identifiers).

When subtracting the image arrays of on-source and off-source mosaic cubes from each other, bear in mind that their spatial dimensions may not be the same as each other. While all pointed observations do have the sky footprint of the PACS IFU (i.e. a 47" square field), in the course of turning them into interpolated cubes they can sometimes end up having very slightly different dimensions (this depends on the position angle of the observation and the need to make a quadrilateral grid). One way to get around this is to re-run the HPDP script to create rebinned cubes, manipulated as required and averaged, do a background subtraction using the pipeline task, and then create the mosaic cube. See Sec. 6.4.2 for more advice.



All HPDP cubes created as part of an on-off pair will have the same wavelength grid (and so that dimension will be the same for the two).

### **6.4.2 Pointed chop-nod observations: one nod position is contaminated**

If only one nod position is contaminated, the advice given in Sec 6.4.1 should be followed with a few differences: rather than averaging together the nodA and nodB off-source cubes, only the one that is clear of contamination should be used, and it will then be necessary to *also* only use that nod position of the on-source data. Therefore the HPDP script (or the ‘Split On-Off’ script in HIPE, on which the HPDP script is based) should be used. At the point where on-source and off-source cubes are selected (selectSlices), only the nod position that is clear of contamination should be selected. The rest of the script can then be followed, ending with an additional background subtraction task (specSubtractOffPosition, which can be taken from one of the unchopped pipeline scripts), and then the recommended mosaic cubes can be created (see the [Quick-Start Guide](#) and the [Product Decision Tree](#) for advice).

This works well if you are interested in emission lines only. If you are also interested in measuring the continuum, note that its flux level of the nodAon-nodAoff (or nodB) will not be correct for the reasons given in Sec. 3.1. However, if the contamination is limited to emission lines, then the continuum level in the SPG cubes will be correct and scientific measurements can be made from those.

Another option – to be followed if you do not want to sacrifice half of the observation – is to manipulate the data of the cube of the contaminated off-source position (e.g. cut out the unwanted lines), average the two off-source cubes, and then subtract that from the on-source cube. This can be done directly on the HPDP cubes if dealing with pointed observations, alternatively on the rebinned cubes, which afterwards can be turned into a mosaic cube you want.

### **6.4.3 Mapping chop-nod observations: both nod positions are contaminated**

Since both nod positions are contaminated, you should combine (average) the nodA and nodB off-source cubes and manipulate the spectra as required (e.g. cut out unwanted lines) before doing an off-source subtraction.

For mapping chop-nod observations, the field covered by the on-source and off-source cubes should have the same dimensions. Hence, in principle the HPDP on-source and off-source cubes can be used: manipulate the image array of the off-source cube and subtract that from the on-source cube. However, subtracting the image arrays of the *mosaic* cubes is not necessarily recommended. It is better to instead use the HPDP script (or the ‘Split On-Off’





script on which these are based) to create rebinned cubes, average together the nod A and nod B off-source cubes, manipulate the spectra as required, and then use the standard pipeline task for unchopped observations (`specSubtractOffPosition`, which can be taken from one of the unchopped pipeline scripts), to do the subtraction of the on-source and off-source rebinned cubes. The resulting residual rebinned cube can then be turned into a mosaic cube (see the [Quick-Start Guide](#) and the [Product Decision Tree](#) for advice on mosaic cubes). The difference between this approach and that of subtracting the HPDP on-source and (manipulated) off-source mosaic cubes directly is an improved SNR and spectral shape. For bright lines this is probably not important, but for middling and fainter lines it could be.

#### **6.4.4 Mapping chop-nod observations: one nod position is contaminated**

If only one nod position is contaminated, the advice given in Sec 6.4.3 should be followed with some differences: rather than averaging together the nodA and nodB off-source cubes, only the one that is clear of contamination should be used, and it will then be necessary to *also* only use that nod position of on-source data. Therefore the HPDP script (or the ‘Split On-Off’ script in HIPE, on which the HPDP script is based) should be used. At the point where on-source and off-source cubes are selected (`selectSlices`), here only the nod position that is clear of contamination should be selected. The rest of the script can then be followed, ending with an additional background subtraction task (`specSubtractOffPosition`, which can be taken from one of the unchopped pipeline scripts), and then the recommended mosaic cubes can be created (see the [Quick-Start Guide](#) and the [Product Decision Tree](#) for advice here).

This works well if you are interested in emission lines only. If you are also interested in measuring the continuum, note that its flux level of the nodAon-nodAoff (or nodB) will not be correct, for the reasons given in Sec. 3.1. However, if the contamination is limited to emission lines, then the continuum level in the SPG cubes will be correct and scientific measurements can be made from those.

Another option – to be followed if you do not want to sacrifice half of the observation – is to manipulate the data of the rebinned cube of the affected off-source position (e.g. cut out the unwanted lines), then average the two off-source rebinned cubes, and then subtract that from the on-source rebinned cube. Mosaic cubes can then be created.

## **7 TESTS SUBTRACTING HPDP ON AND OFF CUBES**

Tests were carried out on the HPDP mosaic cubes, to see how similar the results of subtracting off-source from on-source mosaic cubes would be to working instead with the rebinned cubes and then creating mosaic cubes from the subtracted residual. The second



approach is closer to what is done by the SPG pipeline, and is generally the recommended route: here we tested that recommendation.

One thing to bear in mind if you need to manipulate in some way the data from PACS cubes, is with which datasets and cubes you should work. The mosaic cubes are fairly simple: they have an image and error array, and the wavelength grid is either equidistant (and so encoded in the WCS) or not (and held in an extension in the FITS file). The rebinned cubes have many extensions and are a more complex product (e.g. the spatial grid is not encoded in the WCS). The [PACS Products Explained](#) and can be consulted to learn more about these cubes and their datasets.

## 7.1 Unchopped observations

Tests were carried out on a few HPDP cubes from *unchopped pointed observations* that were clear of off-source contamination. The image arrays of the interpolated cubes were subtracted from each other, and this compared to the SPG products. The idea was to see if doing a background subtraction directly with the HPDP cubes replicates the SPG cubes.

It was found that the resulting HPDP and SPG “residual” cubes had very similar spectra to each other – to the noise level they were almost identical – although some cubes showed slight differences to the absolute level of the continuum. Hence, it is possible to subtract the HPDP off-cube from the HPDP on-cube and expect a result that is the very close to that that provided by the HSA. This is explained by the fact that the interpolation done by the specInterpolate task for pointed observations performs a simple job: interpolating from native spaxels of 9.4” to spatial pixels of 3”, for a single FoV and so crucially with no combining of overlapping spaxels from separate pointings. The only potential technical issue may be that the cubes have different dimensions to each other.

Tests were also carried out on a few HPDP cubes from *unchopped mapping observations* that were clear of off-source contamination, and here much larger differences between the residual of the on- and off-source HPDP cubes and the spectra of the background-subtracted SPG cubes were found. For the observations checked, the most noticeable differences was an additive offset and in its slope/curvature. Differences to the bumps and wiggles in the spectra are also seen, and this in particular *will* affect the determination of the presence of, and the measurements of, spectral lines of even middling SNR. It is therefore not recommended at all to do a subtraction using the HPDP cubes for mapping observations.

## 7.2 Chop-nod observations

With the aim of seeing whether doing a background subtraction using the HPDP cubes produces the same result as the SPG provides, a selection of *chop-nod line- and range-scan pointed observations* were processed in the following way: the image arrays of the HPDP offA



and offB interpolated cubes were averaged and this subtracted from the image array of the HPDP on-source interpolated cube; the spectra were compared, spaxel-by-spaxel, to the spectra in the interpolated cubes taken from the SPG download. Notable differences in the results were found:

- While average level of the continuum was similar for the HPDP and SPG cubes, for some cubes there was a noticeable difference in the shape/slope of their continua.
- The RMS of the SPG spectra was usually better than that of the HPDP spectra; for faint lines this could be important.
- For spectra with emission lines, while in some cases the HPDP and SPG integrated line fluxes (as measured from above the continuum) were similar, in other cases they were not: the spectra show a multiplicative rather than an additive difference in the continuum level and in the line fluxes. As explained in Sec. 2.2.3 and Sec. 4.3.1, this is due to the different way the calibration scheme of the HPDP and SPG scripts deal with the data.

As with the findings for comparing the SPG and HPDP (on-off) cubes for unchopped mapping observations, for *chop-nod mapping observations* it is *additionally* the case that HPDP on-source cubes should not be subtracted from HPDP off-source cubes, but this should rather be done on the rebinned cubes using the appropriate pipeline task and only then should the recommended mosaic cube be created.

## Glossary

**Chop-Nod observing mode:** Two ways were provided by PACS to sample the background from an off position. These are explained in the [PACS Handbook](#). The chop-nod mode was the most used because it produced data with a better continuum reliability and slightly better SNR. In this mode the telescope chopped between an on-source and off-source location at two nod positions.

**HSA:** Herschel Science Archive

**HIPE:** Herschel Interactive Processing Environment

**HPDP:** Highly processed data products

**Mapping observing mode:** Two pointing modes were offered for observing with PACS. Mapping observations were performed as a raster of pointings.

**Mosaic cubes (Interpolated, Projected, Drizzled):** Mosaic cubes are those created by combining individual cubes taken in a mapping observation: separate and slightly-offset pointings combined to observe either a larger field or to improve the spatial sampling of the source. Three mosaicking tasks were provided by the pipeline (specInterpolate, specProject, and drizzle). Which one or two of these tasks were run for each observation depended on the observing mode. All mosaicking tasks created new cubes by combining the data of overlapping spaxels of the input cubes to create the data in the spatial pixels of the output mosaic cube. They differ in the algorithm used to do the mosaicking (see the [PACS Handbook](#) for details). Mosaic cubes are also offered for pointed observations, the reason for this was to create cubes with a regular spatial grid which can load more easily into cube-viewing software.

**Native cube:** used to refer to a cube that has the spatial grid determined only by the instrument. For PACS this is a 5x5 slightly irregular grid with 9.4" spaxels.

**PacsCubes:** The first cube of the pipeline, from which the rebinned cubes are created.

**Pointed observing mode:** Two pointing modes were offered for observing with PACS. Pointed mode observations were on a single FoV.

**RSRF:** relative spectral response function

**Rebinned cubes:** "Rebinned cubes" are the final fully-calibrated native cubes that are produced by the pipeline: one cube per requested wavelength range and, for mapping observations, per raster position. It is from the rebinned cubes that the mosaic cubes are produced – these mosaic cubes being the end product for most mapping observations and one possible end product for pointed observations. (The rebinned cubes have the 5x5 grid of 9.4"-sized spaxels that is the native sky footprint of the PACS IFU, while the spatial grid of the mosaic cubes depends on the mapping field requested by the observer and the size chosen for the mosaicked spatial pixels.)

**SPG:** Standard Product Generator, short-hand for the automatic pipeline run at the HSC for all Herschel observations. The SPG download/products are the "pipeline" products that a user downloads from the HSA after an archive search.

**Spatial Pixel/Spaxel:** Both are the name given to the pixels of a cube, each of which contains a full spectrum for a small patch of sky. The difference is that *spaxel* usually refers to the pixel of a native cube (for PACS that is the rebinned cube) with an area that is determined only by the instrument (i.e. 9.4" for PACS); *spatial pixel* refers to the pixel of a mosaic cube, and it can have any size – the ideal size depends on the mosaicking algorithm and the pointing pattern of the observation (how many overlapping spaxels are there in each spatial pixel?).

**Unchopped observing mode:** Two ways were provided by PACS to sample the background from an off position. These are explained in the [PACS Handbook](#). The Unchopped mode was offered for observations of crowded sources where the off-position had to be especially chosen. A block of on-source was followed by a block of off-source observing.

